

<https://helda.helsinki.fi>

Measurement of the differential inclusive B⁺ hadron cross sections in pp collisions at root s=13TeV

Khachatryan, V.

2017-08-10

Khachatryan , V , Eerola , P , Pekkanen , J , Voutilainen , M , Härkönen , J , Karimäki , V , Kinnunen , R , Lampén , T , Lassila-Perini , K , Lehti , S , Lindén , T , Luukka , P , Tuominiemi , J , Tuovinen , E , Wendland , L , Talvitie , J , Tuuva , T & The CMS Collaboration 2017 , ' Measurement of the differential inclusive B⁺ hadron cross sections in pp collisions at root s=13TeV ' , Physics Letters B , vol. 771 , pp. 435-456 . <https://doi.org/10.1016/j.physletb.2017.05.074>

<http://hdl.handle.net/10138/224282>

<https://doi.org/10.1016/j.physletb.2017.05.074>

cc_by

publishedVersion

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.



Measurement of the differential inclusive B^+ hadron cross sections in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration^{*}

CERN, Switzerland



ARTICLE INFO

Article history:

Received 3 September 2016

Received in revised form 20 May 2017

Accepted 24 May 2017

Available online 30 May 2017

Editor: M. Doser

Keywords:

CMS

Physics

B-physics

ABSTRACT

The differential cross sections for inclusive production of B^+ hadrons are measured as a function of the B^+ transverse momentum p_T^B and rapidity y^B in pp collisions at a centre-of-mass energy of 13 TeV, using data collected by the CMS experiment that correspond to an integrated luminosity of 48.1 pb^{-1} . The measurement uses the exclusive decay channel $B^+ \rightarrow J/\psi K^+$, with J/ψ mesons that decay to a pair of muons. The results show a reasonable agreement with theoretical calculations within the uncertainties.

© 2017 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

Measuring the production of hadrons that contain b quarks plays an important role in testing quantum chromodynamics (QCD). Such studies have been carried out by several experiments, including UA1 [1,2] at CERN, as well as CDF [3–6] and D0 [7,8] at Fermilab. The most recent measurements are from the ATLAS [9,10], CMS [11–17], and LHCb [18–20] Collaborations at the CERN LHC in pp collisions at centre-of-mass energies at 7 and 8 TeV. Similar studies at the higher LHC energy of 13 TeV provide a new test of theoretical calculations [21,22].

This Letter describes a measurement of the inclusive B^+ differential production cross sections as a function of the transverse momentum (p_T^B) and rapidity (y^B) of the B^+ meson (charge conjugation is implied throughout this paper). The analysis is based on data collected at the LHC with 50 ns bunch spacings by the CMS experiment at $\sqrt{s} = 13$ TeV that correspond to an integrated luminosity of 48.1 pb^{-1} . The measurement is based on the inclusive channel $pp \rightarrow B^+ X \rightarrow J/\psi K^+ X$, with the J/ψ mesons decaying into a pair of muons. The measured cross sections are compared to PYTHIA [23] and FONLL [24,25] calculations.

2. The CMS detector and trigger

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field

of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter reside within the magnetic volume of the solenoid. The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. Muons are measured with detectors made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching stubs in the muon system to tracks measured in the silicon tracker result in a transverse momentum (p_T) resolution better than 1.5% for a typical muon in this analysis [26]. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [27].

The triggers have two levels of activation: the first-level (L1) trigger is based on the information provided by the muon detectors, while the “high-level trigger” (HLT) uses information from the silicon tracker to filter the events. Two L1 trigger requirements are used: one requires two muons in the barrel region ($|\eta| < 1.6$), without explicitly imposing a minimum p_T value; the other accepts two muons with relaxed pseudorapidity restrictions (i.e. $|\eta| < 2.4$) but requires at least one muon to have $p_T > 10 \text{ GeV}$. The HLT requires the two muons to be of opposite charge, to lie within $|\eta| < 2.4$, and to have $p_T > 4 \text{ GeV}$. The dimuon invariant mass must be in the range 2.9–3.3 GeV, and the χ^2 probability of the dimuon fit (imposing a common vertex) must be greater than 10%. Furthermore, the signal purity from the trigger is enhanced by requiring the distance between the dimuon vertex and the interaction point (the mean pp collision position or beam spot, which is determined for each set of events collected during a period of 23 seconds) in the transverse plane be larger than three times

^{*} E-mail address: cms-publication-committee-chair@cern.ch.

its uncertainty; this requirement preferentially selects dimuons from “nonprompt” J/ψ meson decays, while rejecting almost all promptly produced J/ψ mesons. Also, the J/ψ meson momentum vector reconstructed at the HLT stage must point back to the interaction point in the transverse plane. This condition is imposed by requiring $\cos(\alpha) > 0.9$, where α is the angle between the J/ψ momentum vector and the vector pointing from the interaction point to the dimuon vertex. Finally, the J/ψ candidate is combined with any other charged particle of $p_T > 0.8$ GeV, and the three-track fit to a common secondary vertex is performed. The HLT requires at least one of the fits to have a χ^2 per degree of freedom smaller than 10.

3. Event reconstruction and selection

The first step in the reconstruction of the $B^+ \rightarrow J/\psi K^+$ decays is the selection of events containing a pair of muons originating from the decay of a J/ψ meson. The muons are required to have at least one reconstructed segment in the muon detectors that matches the extrapolated position of a track reconstructed in the silicon tracker, to satisfy $p_T > 4.2$ GeV, $|\eta| < 2.1$, and to have good quality in the fit to a track. The muon tracks are required to intersect a cylinder of 0.3 cm radius in the transverse plane and 20 cm length along the beam line relative to the interaction point.

Candidate J/ψ mesons are reconstructed by combining pairs of oppositely charged muons having an invariant mass within ± 150 MeV of the nominal J/ψ meson mass [28]. Each J/ψ candidate must have $p_T > 8$ GeV, and a χ^2 probability for a fit to the dimuon vertex larger than 10%. Both muons must be either within $|\eta| < 1.6$ or one of the muons must have $p_T > 11$ GeV. Candidate B^+ mesons are reconstructed by combining a J/ψ candidate with each charged track in the event having $p_T > 1$ GeV. A kaon mass hypothesis is assumed for the tracks and the χ^2 per degree of freedom of the track fit is required to be less than 5. A kinematic fit is performed to the dimuon-track combination, constraining the dimuon mass to the nominal J/ψ mass. The three-track combination must be compatible with having a common vertex with a χ^2 probability larger than 10% and a reconstructed invariant mass, $M_{J/\psi K}$, in the range 5–6 GeV. The significance in the transverse decay length, defined as the distance between the $\mu\mu K$ vertex and the interaction point in the transverse plane, divided by its uncertainty, is required to exceed 3.5. Also, the cosine of the angle between the B^+ candidate momentum and the vector pointing from the interaction point to the $\mu\mu K$ vertex in the transverse plane must be greater than 0.99. Most of the selected B^+ candidates have a transverse decay length greater than 300 μm . Only a small fraction ($< 1\%$) of events contain two reconstructed B^+ candidates; all reconstructed candidates are included in the analysis. This analysis is insensitive to the number of proton–proton interactions occurring in the same or nearby bunch crossings.

The combinatorial background arises from the spurious combination of a promptly produced J/ψ meson or a J/ψ meson from a B hadron decay with an uncorrelated charged particle. The former case is suppressed by the requirement on the reconstructed decay length of the B^+ candidate. Given the excellent dimuon mass resolution at the J/ψ mass and the good muon identification performance of the CMS detector, the background level under the J/ψ peak is very small. Other backgrounds arise from misreconstructed b hadron decays, such as $B \rightarrow J/\psi + \text{hadrons}$ (including, e.g. $J/\psi K^*(892)$), which contribute a broad structure in the mass region $M_{J/\psi K} < 5.15$ GeV. Additional background from Cabibbo–Kobayashi–Maskawa-suppressed $B^+ \rightarrow J/\psi \pi^+$ decays with a mass

misassignment to the pion track forms a tiny excess just above the $J/\psi K^+$ signal.

4. Reconstruction efficiency and acceptance

The detection and trigger efficiencies and the geometrical acceptance are evaluated through Monte Carlo simulation studies using large samples of signal events generated in PYTHIA 8.205 (using the CUETP8M1 tune [29] and the NNPDF2.3 parton distribution functions [30]) and processed by the simulation framework of the CMS detector based on GEANT4 [31]. The decays $B^+ \rightarrow J/\psi K^+$ are modelled with the SVS model of the EVTGEN 1.3.0 [32] generator. The product of the efficiency and acceptance is defined as the fraction of simulated $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ decays, generated in the phase-space region of $10 \leq p_T^B < 17$ GeV and $|y^B| < 1.45$, and in the region of $17 \leq p_T^B < 100$ GeV and $|y^B| < 2.1$, that survive the selection criteria. These values range from 0.8% for $p_T^B \approx 10$ GeV to 20% for $70 < p_T^B < 100$ GeV, and from 3.6% for $|y^B| \approx 0$ to 2.5% for $1.8 < |y^B| < 2.1$.

The trigger and muon reconstruction efficiencies are also measured from a data sample consisting of inclusive $J/\psi \rightarrow \mu^+ \mu^-$ decays, using a technique similar to that described in Ref. [33], where one muon is identified with stringent quality requirements and the second muon is identified using information either from the tracker (to measure the trigger and muon identification efficiencies) or from the external muon system (to measure the silicon tracker efficiency). These efficiencies are compared to those from simulation studies, in bins of muon p_T and η , and are found to agree within their uncertainties. The measured efficiencies of the track reconstruction and of the vertex-quality requirement are also found to be compatible with the simulations.

5. Extraction of the signal

The B^+ differential cross section $d\sigma/dp_T^B$ is measured in 2 bins of p_T^B between 10 and 17 GeV in a restricted y^B range ($|y^B| < 1.45$) and in 7 bins of p_T^B in the extended y^B range ($|y^B| < 2.1$) for p_T^B between 17 and 100 GeV. The corresponding differential cross section $d\sigma/dy^B$ is measured in 6 (2) bins of $|y^B|$ for p_T^B between 10–100 GeV (17–100 GeV). The signal yield is extracted with an extended unbinned maximum-likelihood fit to the invariant mass distribution of the B^+ candidates in each of the p_T^B or $|y^B|$ bins. The signal component is modelled by the sum of two Gaussian functions (representing the “core” and a “tail”). The relative mean of the tail Gaussian function is fixed with respect to that of the core Gaussian function, following the shapes obtained from simulated samples. The relative normalization and width of the tail Gaussian function are also fixed to the parameters obtained from simulated samples for the p_T^B bins above 50 GeV and $|y^B|$ bins above 1.45, to account for the limited size of the data sample. The combinatorial background from the inclusive J/ψ meson production is modelled by an exponential function. The background from misreconstructed $B \rightarrow J/\psi + \text{hadrons}$ decays is represented by an error function. The normalization of misreconstructed $B \rightarrow J/\psi + \text{hadrons}$ decays relative to the signal is determined from a fit to all selected B^+ candidates, and is fixed to this value in the fits that are performed in individual p_T^B or $|y^B|$ bins. The contribution from the decay $B^+ \rightarrow J/\psi \pi^+$ is modelled through a sum of three Gaussian functions; the relative yield of the $J/\psi \pi^+$ to the signal $J/\psi K^+$ is fixed by their decay branching fractions [28]. Fig. 1 shows the invariant mass distribution of all the B^+ candidates, compared to the corresponding sum of the signal and background distributions obtained from the maximum-likelihood fit. Typical invariant mass distributions of the B^+ candidates in one of the p_T^B bins and

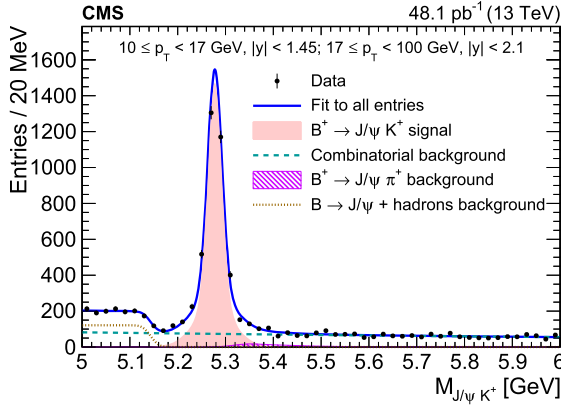


Fig. 1. Invariant mass distribution of $B^+ \rightarrow J/\psi K^+$ candidates, integrated over the phase-space region of $10 \leq p_T^B < 17$ GeV and $|y^B| < 1.45$, and of $17 \leq p_T^B < 100$ GeV and $|y^B| < 2.1$. The solid curve shows the result of the fit. The shaded and hatched areas represent, respectively, the $J/\psi K^+$ signal and the $J/\psi \pi^+$ component, while the dashed and dotted curves represent the combinatorial and misreconstructed $B \rightarrow J/\psi + \text{hadrons}$ backgrounds, respectively.

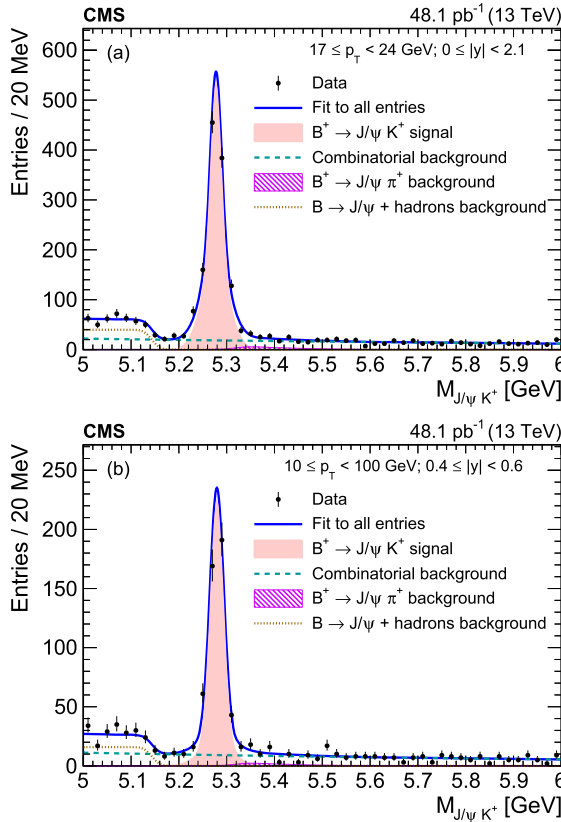


Fig. 2. Invariant mass distributions of the $B^+ \rightarrow J/\psi K^+$ candidates in the regions of (a) $17 \leq p_T^B < 24$ GeV, $|y^B| < 2.1$, and (b) $10 \leq p_T^B < 100$ GeV, $0.4 \leq |y^B| < 0.6$. The solid curve shows the result of the fit. The shaded (hatched) area represents the signal ($B^+ \rightarrow J/\psi K^+$) component, while the dashed and dotted curves represent the combinatorial and misreconstructed $B \rightarrow J/\psi + \text{hadrons}$ background components, respectively.

in one of the $|y^B|$ bins are shown in Fig. 2. The $B^+ \rightarrow J/\psi \pi^+$ background, shown by the hatched area, is centred around 5.4 GeV, but is so small as to be almost invisible in the figures. The dip in the measured invariant mass distributions around 5.17 GeV is caused by the shape of the $B \rightarrow J/\psi + \text{hadrons}$ background distribution, which falls abruptly in that region.

Table 1

Summary of the relative systematic uncertainties in the measured B^+ production cross sections. The ranges given reflect the uncertainties over the p_T^B and y^B bins.

Systematic sources	Relative uncertainties (%)
Muon trigger, identification, and reconstruction	6.0–14
Detector alignment	2.8
B^+ vertex reconstruction	1.4
Size of simulated samples	0.5–3.9
Track reconstruction efficiency	3.9
$B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^+$ branching fraction	3.1
Model in likelihood fits	1.0–6.4
Bin-to-bin migration	0.4–3.7
B^+ kinematic distributions	0.4–11
Parton distribution functions	0.1–0.7
B^+ lifetime	0.3
Total (excluding the integrated luminosity)	9.1–16
Integrated luminosity	2.3

6. Systematic uncertainties

The measured cross section is affected by systematic uncertainties in the extraction of signal, efficiencies, branching fractions, and integrated luminosity, as summarized in Table 1. The dominant effects are associated with the models used in the likelihood fits, the B^+ kinematic distributions, and the estimation of the muon identification and reconstruction. The total uncertainty is evaluated as the sum in quadrature of the individual contributions.

The uncertainty associated with the trigger criteria is evaluated by comparing the trigger efficiencies in data and simulations for an event sample recorded using an inclusive J/ψ trigger with higher- p_T thresholds. The muon identification and reconstruction performances are studied using a large sample of inclusive $J/\psi \rightarrow \mu^+ \mu^-$ events. The efficiencies in data and simulated events are found to be consistent, and residual differences are considered as systematic uncertainties. The uncertainty associated with the alignment of the detector is examined by comparing events simulated with different detector conditions, and assigning an uncertainty of 2.8%. Through a comparison of χ^2 distributions in data and simulations, the uncertainty in the B^+ vertex reconstruction efficiency is estimated to be 1.4%. In addition, the uncertainty coming from the finite size of the simulated samples and a systematic uncertainty of 3.9% in the charged-particle track reconstruction efficiency [34] are also taken into account. The integrated luminosity is measured with an uncertainty of 2.3% [35], while the uncertainty associated with the $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ branching fraction is 3.1% [28].

The systematic uncertainty associated with the modelling of the signal shape is evaluated by changing the model to the sum of three Gaussian functions, or a Gaussian function plus a Crystal Ball function [36]. The uncertainty from the model of the combinatorial background is evaluated by changing the exponential function to a second-order polynomial. The systematic uncertainty associated with the modelling of the mass distribution of misreconstructed $B \rightarrow J/\psi + \text{hadrons}$ events is evaluated by shifting the mass-threshold parameter in the error function by ± 10 MeV. The uncertainty associated with the $B^+ \rightarrow J/\psi \pi^+$ component is estimated by changing its branching fraction by its uncertainty [28], and by shifting its mass value by ± 15 MeV in the likelihood fits. Systematic uncertainties owing to the finite resolution of the reconstructed p_T^B and y^B are determined by examining the generator information in the simulated samples; half of the bin-to-bin-migrated events are taken as the corresponding uncertainty. The uncertainties associated with the p_T^B and y^B distributions in the generation of simulated events are evaluated with event-by-event weights determined from the differences between the distributions in PYTHIA and the FONLL calculations. The latter uses

Table 2

The ranges in p_T^B and $|y^B|$, signal yields n_{sig} , acceptance times efficiency $A\epsilon$, and measured differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$, compared to the FONLL and PYTHIA predictions. The three uncertainties in the measured cross sections refer to the statistical, systematic, and integrated luminosity uncertainties, respectively. The uncertainties in $A\epsilon$ and in the FONLL predictions are the total uncertainties. The last row (“Inclusive bin”) presents the measured total cross section and the FONLL and PYTHIA predictions for the phase-space region of $10 \leq p_T^B < 17$ GeV and $|y^B| < 1.45$, and $17 \leq p_T^B < 100$ GeV and $|y^B| < 2.1$.

p_T^B [GeV]	$ y^B $	n_{sig}	$A\epsilon$ [%]	$d\sigma/dp_T^B$ [$\mu\text{b}/\text{GeV}$]	FONLL [$\mu\text{b}/\text{GeV}$]	PYTHIA [$\mu\text{b}/\text{GeV}$]
10–13	<1.45	408^{+52}_{-53}	0.78 ± 0.10	$3.0 \pm 0.4 \pm 0.4 \pm 0.1$	$1.4^{+0.5}_{-0.4}$	2.6
13–17	<1.45	755^{+47}_{-45}	3.6 ± 0.3	$0.88 \pm 0.05 \pm 0.08 \pm 0.02$	$0.62^{+0.21}_{-0.14}$	1.12
17–24	<2.1	1140^{+40}_{-39}	7.1 ± 0.6	$0.39 \pm 0.01 \pm 0.04 \pm 0.01$	$0.30^{+0.08}_{-0.06}$	0.48
24–30	<2.1	519^{+30}_{-28}	13 ± 1	$0.12 \pm 0.01 \pm 0.01 \pm 0.00$	0.10 ± 0.02	0.14
30–40	<2.1	404^{+24}_{-23}	17 ± 2	$(4.1 \pm 0.2 \pm 0.4 \pm 0.1) \times 10^{-2}$	$(3.3^{+0.6}_{-0.5}) \times 10^{-2}$	4.4×10^{-2}
40–50	<2.1	157 ± 13	20 ± 2	$(1.3 \pm 0.1 \pm 0.2 \pm 0.0) \times 10^{-2}$	$(1.0^{+0.2}_{-0.1}) \times 10^{-2}$	1.3×10^{-2}
50–60	<2.1	49 ± 8	21 ± 2	$(4.0^{+0.7}_{-0.6} \pm 0.5 \pm 0.1) \times 10^{-3}$	$(3.9^{+0.6}_{-0.5}) \times 10^{-3}$	4.5×10^{-3}
60–70	<2.1	23^{+6}_{-5}	21 ± 3	$(1.9^{+0.5}_{-0.4} \pm 0.3 \pm 0.0) \times 10^{-3}$	$(1.7 \pm 0.2) \times 10^{-3}$	1.8×10^{-3}
70–100	<2.1	24^{+5}_{-4}	20 ± 3	$(6.7^{+1.4}_{-1.3} \pm 1.0 \pm 0.2) \times 10^{-4}$	$(5.0 \pm 0.6) \times 10^{-4}$	5.0×10^{-4}
p_T^B [GeV]	$ y^B $	n_{sig}	$A\epsilon$ [%]	$d\sigma/dy^B$ [μb]	FONLL [μb]	PYTHIA [μb]
10–100	0.0–0.2	460^{+43}_{-33}	3.6 ± 0.5	$5.5^{+0.5}_{-0.4} \pm 0.8 \pm 0.1$	$3.2^{+1.1}_{-0.7}$	5.7
10–100	0.2–0.4	511 ± 32	3.8 ± 0.5	$5.7^{+0.3}_{-0.4} \pm 0.8 \pm 0.1$	$3.2^{+1.1}_{-0.7}$	5.7
10–100	0.4–0.6	455^{+28}_{-27}	4.0 ± 0.5	$4.8 \pm 0.3 \pm 0.6 \pm 0.1$	$3.2^{+1.1}_{-0.7}$	5.6
10–100	0.6–0.85	576^{+30}_{-29}	4.4 ± 0.6	$4.5 \pm 0.2 \pm 0.6 \pm 0.1$	$3.1^{+1.1}_{-0.7}$	5.6
10–100	0.85–1.1	622^{+36}_{-35}	4.2 ± 0.6	$5.0 \pm 0.3 \pm 0.7 \pm 0.1$	$3.1^{+1.0}_{-0.7}$	5.4
10–100	1.1–1.45	671^{+42}_{-41}	3.5 ± 0.4	$4.6 \pm 0.3 \pm 0.6 \pm 0.1$	$2.9^{+1.0}_{-0.7}$	5.2
17–100	1.45–1.8	188^{+18}_{-17}	4.4 ± 0.4	$1.05^{+0.10}_{-0.09} \pm 0.11 \pm 0.02$	$0.68^{+0.18}_{-0.13}$	1.05
17–100	1.8–2.1	35 ± 8	1.4 ± 0.2	$0.74^{+0.18}_{-0.16} \pm 0.09 \pm 0.02$	$0.61^{+0.16}_{-0.12}$	0.96
		n_{sig}	$A\epsilon$ [%]	σ [μb]	FONLL [μb]	PYTHIA [μb]
Inclusive bin		3477^{+86}_{-84}	3.9 ± 0.5	$15.3 \pm 0.4 \pm 2.1 \pm 0.4$	$9.9^{+3.3}_{-2.2}$	17.2

a fixed-order perturbative QCD approach, with a next-to-leading-logarithm approximation, and the NNPDF3.0 parton distribution functions [37]. The uncertainty associated with the parton distribution functions is found to be less than 0.7%, which is estimated using the PDF4LHC prescription [38,39] with the uncertainty sets provided by the NNPDF2.3 [30]. The effect of the systematic uncertainty in the B^+ lifetime (0.3%) is also included.

7. Results

The differential cross sections for B^+ production as a function of p_T^B , for $|y^B| < 1.45$, or for $|y^B| < 2.1$, $d\sigma/dp_T^B$, and as a function of $|y^B|$ (averaged for positive and negative rapidity) for $10 < p_T^B < 100$ GeV, or for $17 < p_T^B < 100$ GeV, $d\sigma/dy^B$, are defined as

$$\frac{d\sigma(pp \rightarrow B^+X)}{dp_T^B} = \frac{n_{\text{sig}}(p_T^B)}{2 A(p_T^B) \epsilon(p_T^B) \mathcal{B} \mathcal{L} \Delta p_T^B}, \quad (1)$$

$$\frac{d\sigma(pp \rightarrow B^+X)}{dy^B} = \frac{n_{\text{sig}}(|y^B|)}{2 A(|y^B|) \epsilon(|y^B|) \mathcal{B} \mathcal{L} \Delta y^B},$$

where $n_{\text{sig}}(p_T^B)$ and $n_{\text{sig}}(|y^B|)$ are the signal yields in the p_T^B or $|y^B|$ bins, obtained in the maximum-likelihood fits; and Δp_T^B and $\Delta y^B = 2\Delta|y^B|$ are the corresponding bin widths; \mathcal{L} is the integrated luminosity. The total branching fraction \mathcal{B} is the product of the individual $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.026 \pm 0.031) \times 10^{-3}$ and $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (5.961 \pm 0.033) \times 10^{-2}$ values [28]. The factor of two in the denominator reflects the choice used to quote the cross section for a single charge (taken to be the B^+), where n_{sig} includes both charge states. Efficiencies and signal yields for B^+ and B^- are found to be compatible within uncertainties. The products of efficiency and acceptance, $A(p_T^B) \epsilon(p_T^B)$ and $A(|y^B|) \epsilon(|y^B|)$, are calculated for each bin.

Table 2 summarizes the event yields, efficiencies, and the differential cross sections for the various p_T^B and y^B bins. The differential cross sections as a function of p_T^B , integrated over $|y^B| < 1.45$ or over $|y^B| < 2.1$, and as a function of y^B , integrated over $10 < p_T^B < 100$ GeV or over $17 < p_T^B < 100$ GeV, are shown in Fig. 3 (a) and (b), respectively, where they are compared to FONLL [24,25] (shaded boxes) and PYTHIA (dashed lines) calculations. The uncertainties in the FONLL calculations include the effects from the renormalization and factorization scales, the mass of the bottom quark, and the uncertainties in the parton distribution functions, which are calculated according to the NNPDF3.0 uncertainty sets [37]. The bottom panels display the ratio of the data to the FONLL predictions; the ratios of the PYTHIA to the FONLL calculations are shown as dashed lines. The previous CMS measurements from $\sqrt{s} = 7$ TeV data [11] are presented as a function of p_T^B , scaled to the phase-space region of $|y^B| < 2.1$ or $|y^B| < 1.45$, and as a function of y^B , scaled to $10 < p_T^B < 100$ GeV or $17 < p_T^B < 100$ GeV. The extrapolations are carried out using the kinematic distributions from generated PYTHIA events, and an additional systematic uncertainty is included based on a comparison of extrapolations obtained with PYTHIA to those obtained with FONLL. Measurements are in good agreement with the theoretical predictions of both FONLL and PYTHIA at high p_T^B , while, at low p_T^B , the measurements tend to favour a higher cross section than estimated by FONLL and smaller than estimated by PYTHIA. The differential cross section as a function of $|y^B|$ is in agreement with both predictions, within the uncertainties. The ratios of the differential cross section measurements at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV, as well as the FONLL and PYTHIA calculations, are shown in Fig. 4. The correlated uncertainties, including muon identification, decay branching fractions, tracking and vertexing, cancel out or are reduced in the evaluations of the ratios, and the measurements prefer higher values compared to the predictions along both p_T^B and $|y^B|$.

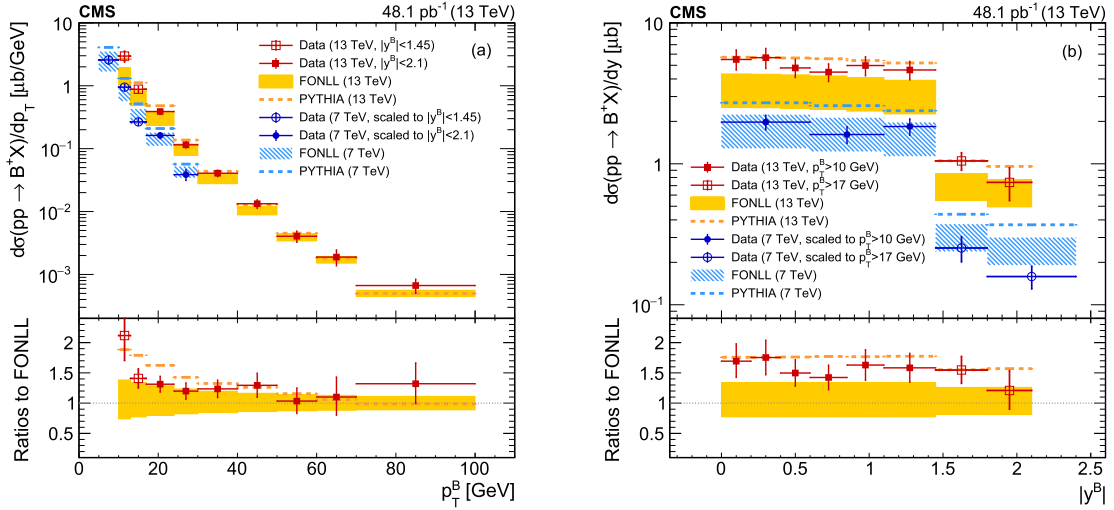


Fig. 3. B^+ differential production cross sections (a) $d\sigma/dp_T^B$ for $|y^B| < 1.45$ or $|y^B| < 2.1$, and (b) $d\sigma/dy^B$ for $10 < p_T^B < 100 \text{ GeV}$ or $17 < p_T^B < 100 \text{ GeV}$, at $\sqrt{s} = 13 \text{ TeV}$ (squares, this measurement). The previous CMS measurements from $\sqrt{s} = 7 \text{ TeV}$ data [11] (circles) are also presented as a function of p_T^B (y^B), scaled to the phase-space region of $|y^B| < 2.1$ or $|y^B| < 1.45$ ($10 < p_T^B < 100 \text{ GeV}$ or $17 < p_T^B < 100 \text{ GeV}$). The vertical bars show the total uncertainty in the measured cross sections, and the horizontal bars represent the bin width. The calculations from FONLL and PYTHIA are shown as shaded boxes and dashed lines, respectively. The bottom panels display the ratio of the data at 13 TeV to the FONLL predictions (points) and the ratios of the PYTHIA to the FONLL calculations (dashed lines), with the shaded region displaying the uncertainties in the FONLL predictions.

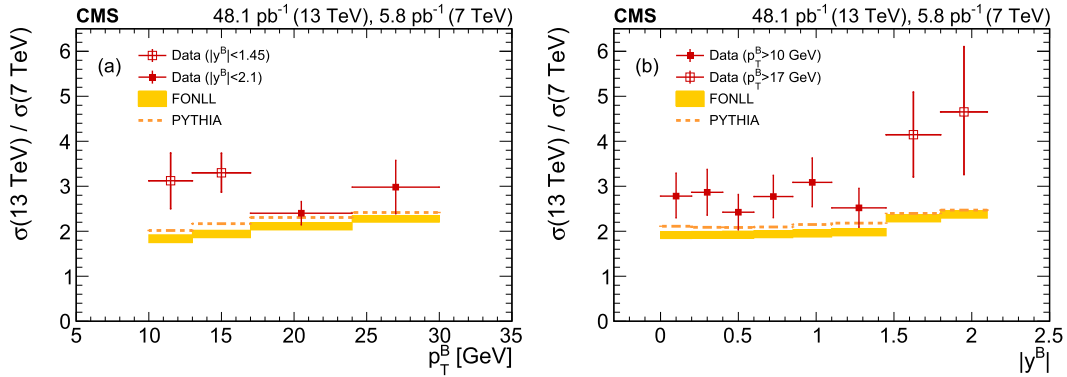


Fig. 4. Ratios of B^+ differential production cross sections at $\sqrt{s} = 13 \text{ TeV}$ and at $\sqrt{s} = 7 \text{ TeV}$ as (a) a function of p_T^B for $|y^B| < 1.45$ or $|y^B| < 2.1$ and (b) as a function of y^B for $10 < p_T^B < 100 \text{ GeV}$ or $17 < p_T^B < 100 \text{ GeV}$. The vertical bars show the total uncertainty in the measured ratios of the cross sections, and the horizontal bars represent the bin width. The calculations from FONLL and PYTHIA are shown as shaded boxes and dashed lines, respectively.

8. Summary

The differential cross sections for B^+ meson production in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ have been measured for the first time by the CMS experiment using the decay channel $B^+ \rightarrow J/\psi K^+$, with $J/\psi \rightarrow \mu^+ \mu^-$, as a function of p_T^B for $|y^B| < 1.45$ or $|y^B| < 2.1$, and as a function of y^B for $10 < p_T^B < 100 \text{ GeV}$ or $17 < p_T^B < 100 \text{ GeV}$. The total cross section summed over all bins is measured to be $15.3 \pm 0.4(\text{stat}) \pm 2.1(\text{syst}) \pm 0.4(\text{lumi}) \mu\text{b}$. The measured distributions show reasonable agreement in terms of shape, as well as normalization, with FONLL calculations and with the prediction of the PYTHIA event generator, within the uncertainties. The ratios between the measurements at 13 and at 7 TeV tend to prefer higher values compared to the predictions. This study provides the first measurement of a b hadron cross section through the $B^+ \rightarrow J/\psi K^+$ exclusive decay channel at the centre-of-mass energy of 13 TeV.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the

technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss

Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References

- [1] C. Albajar, et al., UA1 Collaboration, Beauty production at the CERN proton–antiproton collider, *Phys. Lett. B* 186 (1987) 237, [http://dx.doi.org/10.1016/0370-2693\(87\)90287-5](http://dx.doi.org/10.1016/0370-2693(87)90287-5).
- [2] C. Albajar, et al., UA1 Collaboration, Measurement of the bottom quark production cross section in proton–antiproton collisions at $\sqrt{s} = 0.63$ TeV, *Phys. Lett. B* 213 (1988) 405, [http://dx.doi.org/10.1016/0370-2693\(88\)91785-6](http://dx.doi.org/10.1016/0370-2693(88)91785-6).
- [3] F. Abe, et al., CDF Collaboration, Measurement of the B meson differential cross-section, $d\sigma/dp_T$, in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. Lett.* 75 (1995) 1451, <http://dx.doi.org/10.1103/PhysRevLett.75.1451>, arXiv:hep-ex/9503013.
- [4] D.E. Acosta, et al., CDF Collaboration, Measurement of the B^+ total cross section and B^+ differential cross section $d\sigma/dp_T$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. D* 65 (2002) 052005, <http://dx.doi.org/10.1103/PhysRevD.65.052005>, arXiv:hep-ph/0111359.
- [5] D.E. Acosta, et al., CDF Collaboration, Measurement of the J/ψ meson and b-hadron production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.960$ GeV, *Phys. Rev. D* 71 (2005) 032001, <http://dx.doi.org/10.1103/PhysRevD.71.032001>, arXiv:hep-ex/0412071.
- [6] A. Abulencia, et al., CDF Collaboration, Measurement of the B^+ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.960$ GeV, *Phys. Rev. D* 75 (2007) 012010, <http://dx.doi.org/10.1103/PhysRevD.75.012010>, arXiv:hep-ex/0612015.
- [7] S. Abachi, et al., D0 Collaboration, Inclusive μ and b quark production cross-sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. Lett.* 74 (1995) 3548, <http://dx.doi.org/10.1103/PhysRevLett.74.3548>.
- [8] B. Abbott, et al., D0 Collaboration, Cross section for b jet production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. Lett.* 85 (2000) 5068, <http://dx.doi.org/10.1103/PhysRevLett.85.5068>, arXiv:hep-ex/0008021.
- [9] ATLAS Collaboration, Measurement of the b-hadron production cross section using decays to $D^*\mu^-X$ final states in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *Nucl. Phys. B* 864 (2012) 341, <http://dx.doi.org/10.1016/j.nuclphysb.2012.07.009>, arXiv:1206.3122.
- [10] ATLAS Collaboration, Measurement of the differential cross-section of B^+ meson production in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS, *J. High Energy Phys.* 10 (2013) 042, [http://dx.doi.org/10.1007/JHEP10\(2013\)042](http://dx.doi.org/10.1007/JHEP10(2013)042), arXiv:1307.0126.
- [11] CMS Collaboration, Measurement of the B^+ production cross section in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. Lett.* 106 (2011) 112001, <http://dx.doi.org/10.1103/PhysRevLett.106.112001>, arXiv:1101.0131.
- [12] CMS Collaboration, Inclusive b-hadron production cross section with muons in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 03 (2011) 090, [http://dx.doi.org/10.1007/JHEP03\(2011\)090](http://dx.doi.org/10.1007/JHEP03(2011)090), arXiv:1101.3512.
- [13] CMS Collaboration, Measurement of the B^0 production cross section in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. Lett.* 106 (2011) 252001, <http://dx.doi.org/10.1103/PhysRevLett.106.252001>, arXiv:1104.2892.
- [14] CMS Collaboration, Measurement of the B_s^0 production cross section with $B_s^0 \rightarrow J/\psi\phi$ decays in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. D* 84 (2011) 052008, <http://dx.doi.org/10.1103/PhysRevD.84.052008>, arXiv:1106.4048.
- [15] CMS Collaboration, Measurement of the Λ_b cross section and the $\bar{\Lambda}_b$ to Λ_b ratio with $J/\psi\Lambda$ decays in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Lett. B* 714 (2012) 136, <http://dx.doi.org/10.1016/j.physletb.2012.05.063>, arXiv:1205.0594.
- [16] CMS Collaboration, Measurement of the cross section for production of $b\bar{b}X$, decaying to muons in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 06 (2012) 110, [http://dx.doi.org/10.1007/JHEP06\(2012\)110](http://dx.doi.org/10.1007/JHEP06(2012)110), arXiv:1203.3458.
- [17] CMS Collaboration, Measurement of the ratio of the production cross sections times branching fractions of $B_c^\pm \rightarrow J/\psi\pi^\pm$ and $B^\pm \rightarrow J/\psi K^\pm$ and $B(B_c^\pm \rightarrow J/\psi\pi^\pm\pi^\pm\pi^\mp)/B(B_c^\pm \rightarrow J/\psi\pi^\pm)$ in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 01 (2015) 063, [http://dx.doi.org/10.1007/JHEP01\(2015\)063](http://dx.doi.org/10.1007/JHEP01(2015)063), arXiv:1410.5729.
- [18] LHCb Collaboration, Measurement of the B^\pm production cross-section in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 04 (2012) 093, [http://dx.doi.org/10.1007/JHEP04\(2012\)093](http://dx.doi.org/10.1007/JHEP04(2012)093), arXiv:1202.4812.
- [19] LHCb Collaboration, Measurement of B meson production cross-sections in proton–proton collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 08 (2013) 117, [http://dx.doi.org/10.1007/JHEP08\(2013\)117](http://dx.doi.org/10.1007/JHEP08(2013)117), arXiv:1306.3663.
- [20] LHCb Collaboration, Measurement of B_c^\pm production in proton–proton collisions at $\sqrt{s} = 8$ TeV, *Phys. Rev. Lett.* 114 (2015) 132001, <http://dx.doi.org/10.1103/PhysRevLett.114.132001>, arXiv:1411.2943.
- [21] LHCb Collaboration, Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* 10 (2015) 172, [http://dx.doi.org/10.1007/JHEP10\(2015\)172](http://dx.doi.org/10.1007/JHEP10(2015)172), arXiv:1509.00771.
- [22] LHCb Collaboration, Measurement of the b-quark production cross-section in 7 and 13 TeV pp collisions, *Phys. Rev. Lett.* 118 (2017) 052002, <http://dx.doi.org/10.1103/PhysRevLett.118.052002>, arXiv:1612.05140.
- [23] T. Sjöstrand, S. Mrenna, P.Z. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* 178 (2008) 852, <http://dx.doi.org/10.1016/j.cpc.2008.01.036>, arXiv:0710.3820.
- [24] M. Cacciari, M. Greco, P. Nason, The p_T spectrum in heavy flavor hadroproduction, *J. High Energy Phys.* 05 (1998) 007, <http://dx.doi.org/10.1088/1126-6708/1998/05/007>, arXiv:hep-ph/9803400.
- [25] M. Cacciari, S. Frixione, P. Nason, The p_T spectrum in heavy flavor photoproduction, *J. High Energy Phys.* 03 (2001) 006, <http://dx.doi.org/10.1088/1126-6708/2001/03/006>, arXiv:hep-ph/0102134.
- [26] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, *J. Instrum.* 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [27] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [28] Particle Data Group, K.A. Olive, et al., Review of particle physics, *Chin. Phys. C* 38 (2014) 090001, <http://dx.doi.org/10.1088/1674-1137/38/9/090001> (and 2015 update).
- [29] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* 76 (2016) 155, <http://dx.doi.org/10.1140/epjc/s10052-016-3988-x>, arXiv:1512.00815.
- [30] R.D. Ball, V. Bertone, S. Carrazza, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J. Rojo, NNPDF Collaboration, Parton distributions with QED corrections, *Nucl. Phys. B* 877 (2013) 290, <http://dx.doi.org/10.1016/j.nuclphysb.2013.10.010>, arXiv:1308.0598.
- [31] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.* 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [32] D.J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.* 462 (2001) 152, [http://dx.doi.org/10.1016/S0168-9002\(01\)00089-4](http://dx.doi.org/10.1016/S0168-9002(01)00089-4).
- [33] CMS Collaboration, Prompt and non-prompt J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV, *Eur. Phys. J. C* 71 (2011) 1575, <http://dx.doi.org/10.1140/epjc/s10052-011-1575-8>, arXiv:1011.4193.
- [34] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <http://dx.doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [35] CMS Collaboration, CMS Luminosity Measurement for the 2015 Data Taking Period, CMS Physics Analysis Summary, CMS-PAS-LUM-15-001, 2016, <https://cds.cern.ch/record/2138682>.
- [36] T. Skwarnicki, A Study of the Radiative Cascade Transitions Between the Υ' and Υ Resonances, Ph.D. thesis, DESY-F31-86-02, INP, Cracow, 1986, <https://inspirehep.net/record/230779>.
- [37] R.D. Ball, et al., NNPDF Collaboration, Parton distributions for the LHC Run II, *J. High Energy Phys.* 04 (2015) 040, [http://dx.doi.org/10.1007/JHEP04\(2015\)040](http://dx.doi.org/10.1007/JHEP04(2015)040), arXiv:1410.8849.
- [38] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov, J. Huston, R. McNulty, T. Sjöstrand, R.S. Thorne, The PDF4LHC Working Group interim recommendations, arXiv:1101.0538, 2011.
- [39] S. Alekhin, et al., The PDF4LHC Working Group interim report, arXiv:1101.0536, 2011.

The CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko,

T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang²

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöffbeck, A. Sharma, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, C. Beluffi³, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁴, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja^a, C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^a, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas

^a Universidade Estadual Paulista, São Paulo, Brazil

^b Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁶

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen⁷, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger⁸, M. Finger Jr.⁸

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A. Ellithi Kamel⁹, M.A. Mahmoud^{10,11}, A. Radi^{11,12}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram¹³, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹³, X. Coubez, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, A.-C. Le Bihan, K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁴, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili¹⁵

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze⁸

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov¹⁴

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

V. Cherepanov, G. Flügge, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl¹⁶

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, C. Asawatangkuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras¹⁷, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁹, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁶, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Fries, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann¹⁶, S.M. Heindl, U. Husemann, I. Katkov¹⁴, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioánnina, Ioánnina, Greece

N. Filipovic

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath²⁰, F. Sikler, V. Veszpremi, G. Vesztergombi²¹, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók²¹, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S. Bahinipati, S. Choudhury²³, P. Mal, K. Mandal, A. Nayak²⁴, D.K. Sahoo, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁶, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhowmik²⁵, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, A. Rane, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

H. Behnamian, S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, A. Fahim²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁹, F. Rezaei Hosseinabadi, B. Safarzadeh³⁰, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^{a,16}, R. Venditti^{a,b}, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b,16}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, L. Viliani^{a,b,16}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁶

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, M.R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

L. Brianza¹⁶, M.E. Dinardo^{a,b}, P. Dini^a, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti, S. Malvezzi^a, R.A. Manzoni^{a,b,16}, B. Marzocchi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, S. Pigazzini, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, G. De Nardo, S. Di Guida^{a,d,16}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, F. Thyssen

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^{a,16}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, F. Montecassiano^a, M. Passaseo^a, J. Pazzini^{a,b,16}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, S. Ventura^a, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri^a, A. Magnani^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov^{a,31}, P. Azzurri^{a,16}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,31}, R. Dell'Orso^a, S. Donato^{a,c}, G. Fedì, A. Giassi^a, M.T. Grippo^{a,31}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,32}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, G. D'imperio^{a,b,16}, D. Del Re^{a,b,16}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c,16}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, R. Covarelli^{a,b}, P. De Remigis^a, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, G. Mazza^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b},

M.M. Obertino ^{a,b}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^a, G.L. Pinna Angioni ^{a,b}, F. Ravera ^{a,b},
A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, V. Sola ^a, A. Solano ^{a,b}, A. Staiano ^a, P. Traczyk ^{a,b}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, C. La Licata ^{a,b}, A. Schizzi ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim,
S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali ³³, F. Mohamad Idris ³⁴, W.A.T. Wan Abdullah,
M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz ³⁵, A. Hernandez-Almada,
R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

S. Carpitenteyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico***D. Krofcheck***University of Auckland, Auckland, New Zealand***P.H. Butler***University of Canterbury, Christchurch, New Zealand***A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas***National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan***H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski***National Centre for Nuclear Research, Swierk, Poland***K. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak***Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland***P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia***Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal***V. Alexakhin, A. Golunov, I. Golutvin, N. Gorbounov, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{37,38}, V.V. Mitsyn, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, E. Tikhonenko, N. Voytishin, A. Zarubin***Joint Institute for Nuclear Research, Dubna, Russia***L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev***Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia***Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tisov, A. Toropin***Institute for Nuclear Research, Moscow, Russia***V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin***Institute for Theoretical and Experimental Physics, Moscow, Russia***A. Bylinkin³⁸***Moscow Institute of Physics and Technology, Russia***M. Chadeeva⁴¹, R. Chistov⁴¹, M. Danilov⁴¹***National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia***V. Andreev, M. Azarkin³⁸, I. Dremin³⁸, M. Kirakosyan, A. Leonidov³⁸, S.V. Rusakov, A. Terkulov***P.N. Lebedev Physical Institute, Moscow, Russia*

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴², L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov⁴³, Y. Skovpen⁴³

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴⁵, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁶, M.J. Kortelainen, K. Kousouris, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas⁴⁷, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckalns⁴⁸, G.I. Veres²¹, N. Wardle, H.K. Wöhri, A. Zagozdinska³⁶, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁴⁹, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵⁰, L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

S. Cerci⁵¹, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁵², O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵³, K. Ozdemir⁵⁴, D. Sunar Cerci⁵¹, B. Tali⁵¹, H. Topakli⁵⁵, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Cukurova University, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁶, G. Karapinar⁵⁷, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, E.A. Yetkin⁶⁰, T. Yetkin⁶¹

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶²

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk, P. Sorokin

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶³, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶⁴, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas⁶³, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁴⁹, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁵, T. Virdee¹⁶, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, M. Tadel, A. Vartak, S. Wasserbaech⁶⁶, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, J. Yoo

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. McDermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir[†], M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶⁷, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi⁶⁸, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki⁶⁹, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, C. Bruner, J. Castle, L. Forthomme, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, S. Khalil, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, R. Bartek, K. Bloom, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

A. Agapitos, J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷³, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P.R. Duerdo, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin - Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

³ Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

⁴ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁵ Also at Universidade Federal de Pelotas, Pelotas, Brazil.

⁶ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁷ Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

⁸ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁹ Also at Cairo University, Cairo, Egypt.

¹⁰ Also at Fayoum University, El-Fayoum, Egypt.

¹¹ Now at British University in Egypt, Cairo, Egypt.

¹² Now at Ain Shams University, Cairo, Egypt.

¹³ Also at Université de Haute Alsace, Mulhouse, France.

¹⁴ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

¹⁵ Also at Tbilisi State University, Tbilisi, Georgia.

¹⁶ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

¹⁷ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

¹⁸ Also at University of Hamburg, Hamburg, Germany.

¹⁹ Also at Brandenburg University of Technology, Cottbus, Germany.

²⁰ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

²¹ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

²² Also at University of Debrecen, Debrecen, Hungary.

²³ Also at Indian Institute of Science Education and Research, Bhopal, India.

²⁴ Also at Institute of Physics, Bhubaneswar, India.

²⁵ Also at University of Visva-Bharati, Santiniketan, India.

²⁶ Also at University of Ruhuna, Matara, Sri Lanka.

²⁷ Also at Isfahan University of Technology, Isfahan, Iran.

²⁸ Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

²⁹ Also at Yazd University, Yazd, Iran.

³⁰ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

³¹ Also at Università degli Studi di Siena, Siena, Italy.

³² Also at Purdue University, West Lafayette, USA.

³³ Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

³⁴ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

³⁵ Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

³⁶ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

³⁷ Also at Institute for Nuclear Research, Moscow, Russia.

³⁸ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

³⁹ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

⁴⁰ Also at University of Florida, Gainesville, USA.

⁴¹ Also at P.N. Lebedev Physical Institute, Moscow, Russia.

⁴² Also at California Institute of Technology, Pasadena, USA.

⁴³ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

⁴⁴ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

⁴⁵ Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.

⁴⁶ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

⁴⁷ Also at National and Kapodistrian University of Athens, Athens, Greece.

⁴⁸ Also at Riga Technical University, Riga, Latvia.

⁴⁹ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

⁵⁰ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

⁵¹ Also at Adiyaman University, Adiyaman, Turkey.

⁵² Also at Mersin University, Mersin, Turkey.

⁵³ Also at Cag University, Mersin, Turkey.

⁵⁴ Also at Piri Reis University, Istanbul, Turkey.

⁵⁵ Also at Gaziosmanpasa University, Tokat, Turkey.

⁵⁶ Also at Ozyegin University, Istanbul, Turkey.

⁵⁷ Also at Izmir Institute of Technology, Izmir, Turkey.

⁵⁸ Also at Marmara University, Istanbul, Turkey.

⁵⁹ Also at Kafkas University, Kars, Turkey.

⁶⁰ Also at Istanbul Bilgi University, Istanbul, Turkey.

⁶¹ Also at Yildiz Technical University, Istanbul, Turkey.

⁶² Also at Hacettepe University, Ankara, Turkey.

⁶³ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

⁶⁴ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

⁶⁵ Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.

⁶⁶ Also at Utah Valley University, Orem, USA.

⁶⁷ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

⁶⁸ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

⁶⁹ Also at Argonne National Laboratory, Argonne, USA.

⁷⁰ Also at Erzincan University, Erzincan, Turkey.

⁷¹ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

⁷² Also at Texas A&M University at Qatar, Doha, Qatar.

⁷³ Also at Kyungpook National University, Daegu, Republic of Korea.